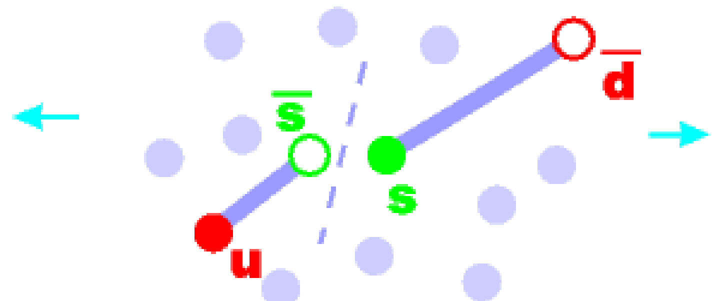
Balance Functions, a Signal of Late-Stage Hadronization

S. Bass, P. Danielewicz and S.P. PRL85, 2689 (2000)

Hadronic Scenario

- **Hadronization @ 1 fm/c**
- **Flux tube and high velocity gradient separate charges**
- $Y_+ - Y_- \sim 1$

QGP Scenario



- **Hadronization @ 5-10 fm/c**
- **Most $q\bar{q}$ pairs created at hadronization**
- $Y_+ - Y_- \sim (T/m)^{1/2} \sim 0.5$

***B*(D*y*) identifies balancing charges statistically**

$$B(\Delta y) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_+} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_-}\right\}$$

Why Charge is Created at Hadronization

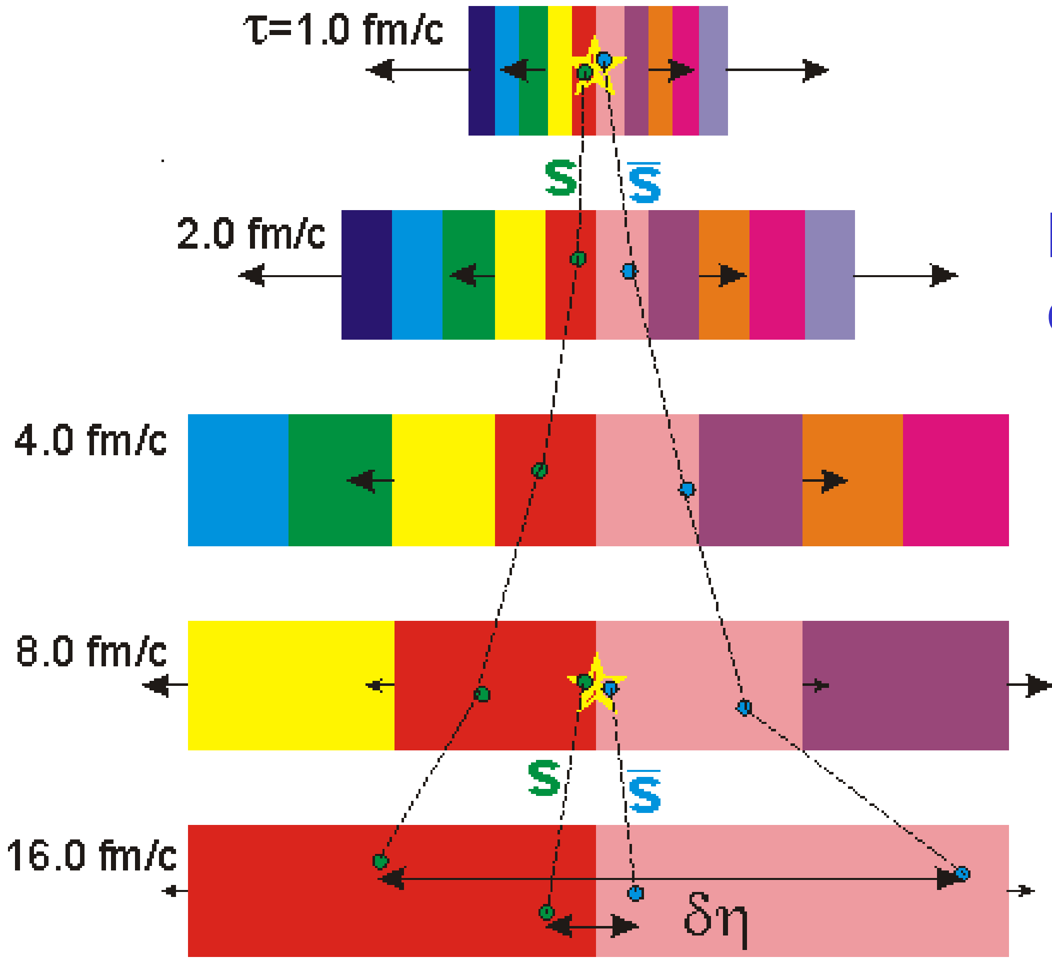
1. **Gluonic modes carry entropy, but no charge**
2. **Coalescence of quarks at same *T* should have:**

$$N_{\text{mesons}} \approx N_q + N_{\bar{q}}$$

→ quark number doubles

3. **Coherent sources (chiral fields, bag energy…) can produce new charge.**

Over half of electric charge, strangeness and antibaryons should be created at hadronization!



If one knows breakup *T*, one can determine s_{dh}

Difficulty:
Identifying balancing partners

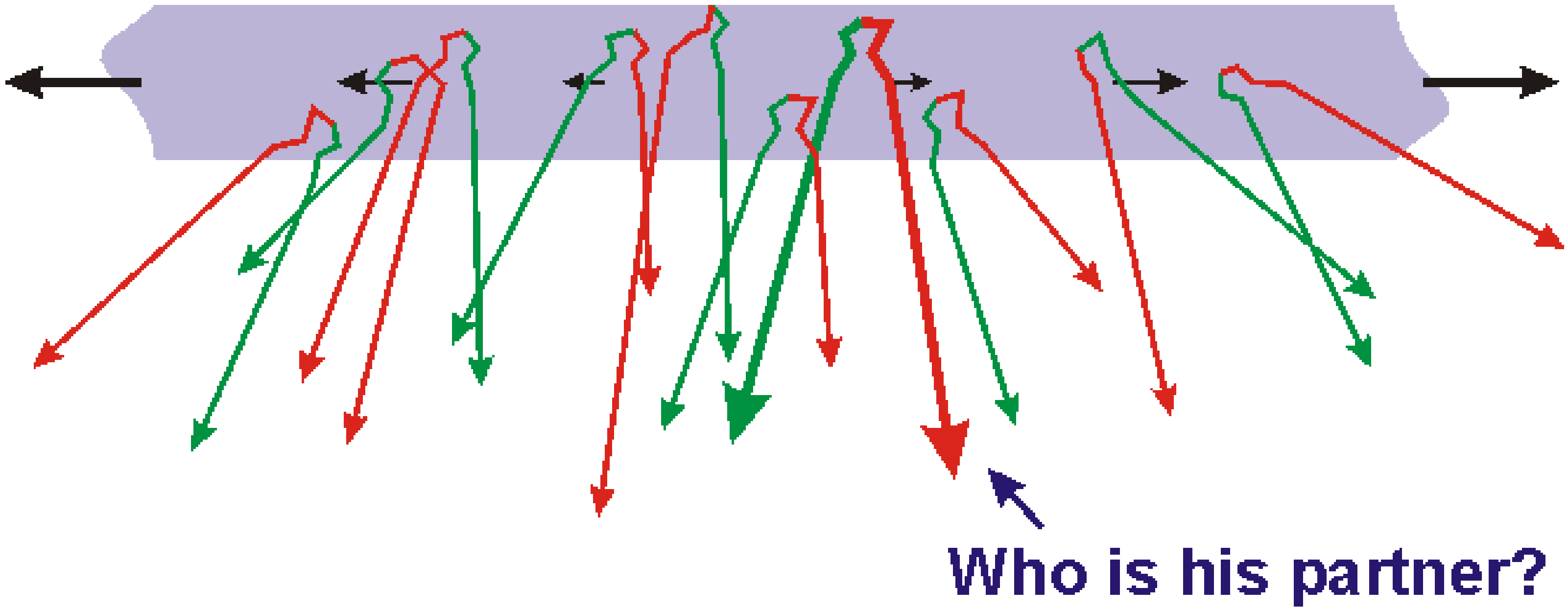
$$\sigma^2_{\delta y} = \sigma^2_{\delta\eta} + \sigma^2_{\text{therm}}$$

experiment

diffusive

determined by breakup temp.

Balance Functions: How They Work



For each charge +*Q*, there is one extra balancing charge –*Q*.

$$B(\Delta y) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_{+}} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_{-}}\right\}$$

Charges: electric, strangeness, baryon number

Balance Function: Properties

In general, $B(P_2|P_1)$ is 6-d object:

$$B(P_2|P_1) \equiv \frac{1}{2}\{D(-,P_2|+,P_1) - D(+,P_2|+,P_1) + D(+,P_2|-,P_1) - D(-,P_2|-,P_1)\}$$

$$D(Q_2,P_2|Q_1,P_1) \equiv \frac{\int_{P_1} d^3p_a \int_{P_2} d^3p_b\; n_2(Q_2,p_b;Q_1,p_a)}{\int_{P_1} d^3p_a n(Q_1,p_a)}$$

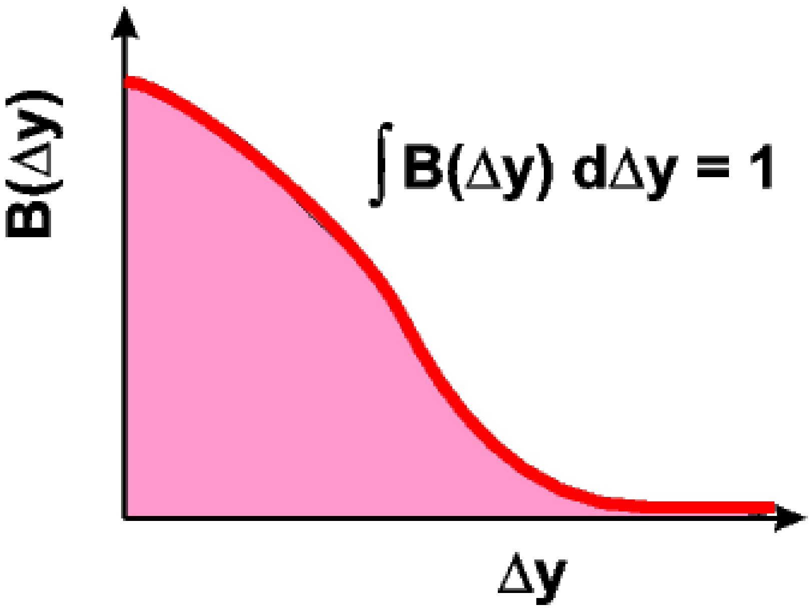
P_2 can refer to any function of p_a and p_b.

Simple Example:

P_1 → anywhere in the detector

P_2 → relative rapidity

Balance Function: Properties



If chance of finding balancing charge = 100%,

→ normalizes to unity:

$$\sum_{P_2} B(P_2|P_1) = 1.$$

True even when áQñ ¹ 0.

Normalization reduced for:

- **Imperfect Acceptance**
- **Loss of Charge through other channels,**

e.g., p$^+$ balanced by K$^-$.

Balance Function: Properties

Relation between Balance Function and *Q* Fluctuations:

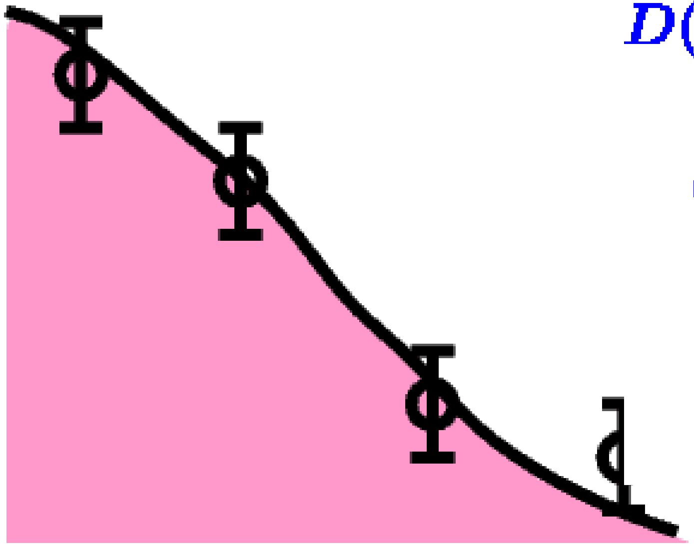
S.Jeon and S.P., in prep.

$$\frac{\langle Q^2 \rangle}{\langle N_+ + N_- \rangle} = 1 - \int_0^\Delta dy B(y)(1 - y/\Delta).$$

- Similar relation between *C(y)* and *F_2(D)*. Wieand et al., PLB (89)
- *B(y)* more physically transparent.
- Each pair contributes ONCE and ONLY ONCE.
- Easier to analyze errors.

Balance Function: Properties

Statistical Errors:



$$D(Q_2, P_2 | Q_1, P_1) = \frac{N(Q_2, P_2; Q_1, P_1)}{N(Q_1, P_1)}$$

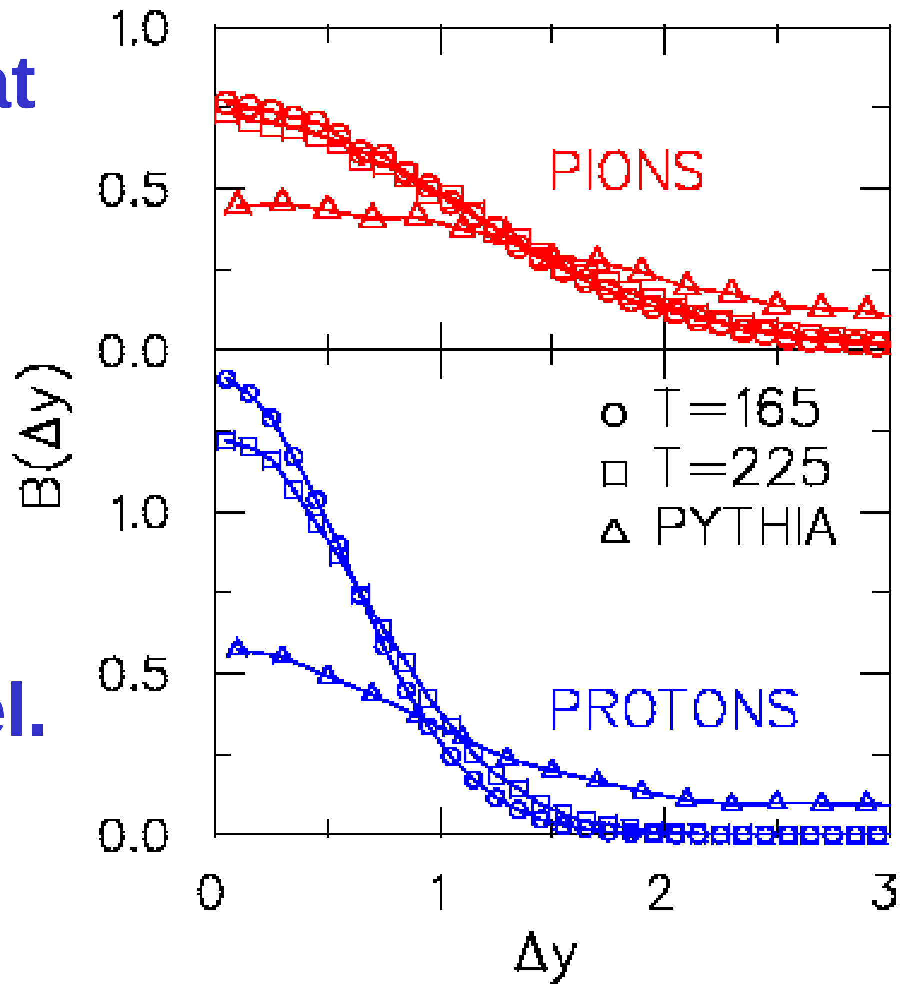
$$\text{Counts in Numerator} \propto M^2 N_{\text{events}}.$$
$$\text{Denominator} \propto M N_{\text{events}}$$

$$\sigma \propto \frac{1}{\sqrt{N_{\text{events}}}}.$$

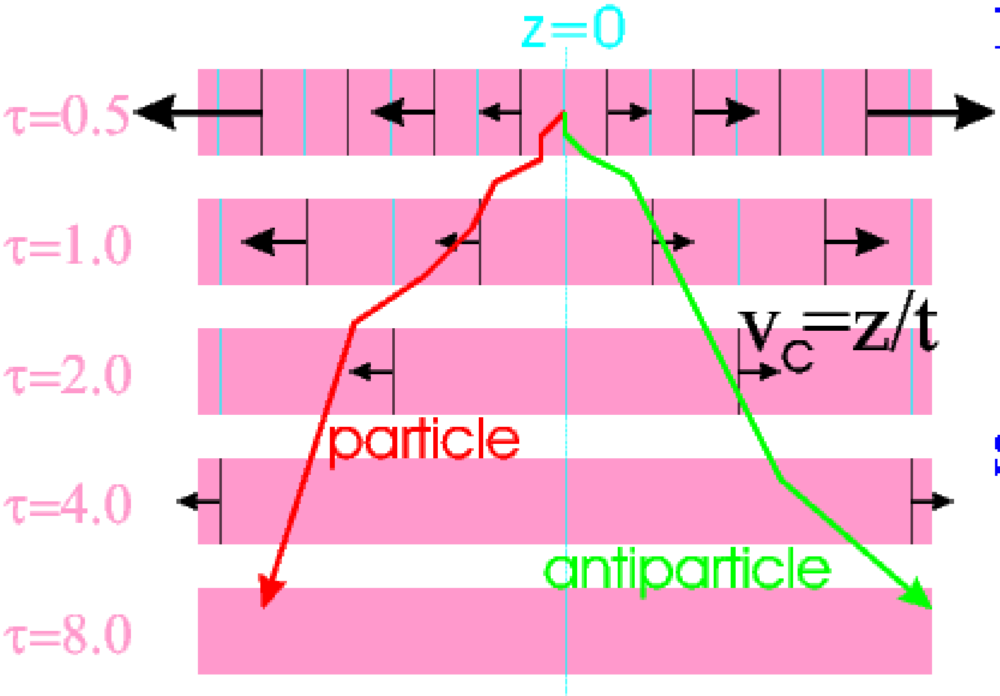
- **Error independent of multiplicity**
- ***KK***, pp, $p\bar{p}$ **have ~ same error**
- **number events determined by chance of observing balancing charge.**

Thermal Model

- **Assume $\bar{Q}$ & Q produced at same point.**
- **áD*y*ñ determined only by *T* and *m*.**
- **Proton balance function narrower that pion's.**
- **Thermal model always narrower than string model.**



Diffusion: An Analytic Picture



Diffusion Eq:

$$\frac{\partial}{\partial \tau} f(\tau,\eta) = -\frac{\beta}{\tau}\frac{\partial^2}{\partial \eta^2} f(\tau,\eta).$$

$$\beta = \frac{1}{n\tau\sigma v_{\rm therm}}.$$

Solution:

$$f(\tau,\eta) \sim \exp\left(-\frac{\eta^2}{2\sigma_\eta^2}\right)$$

$$\sigma_\eta = 2\beta \log\frac{\tau}{\tau_0}$$

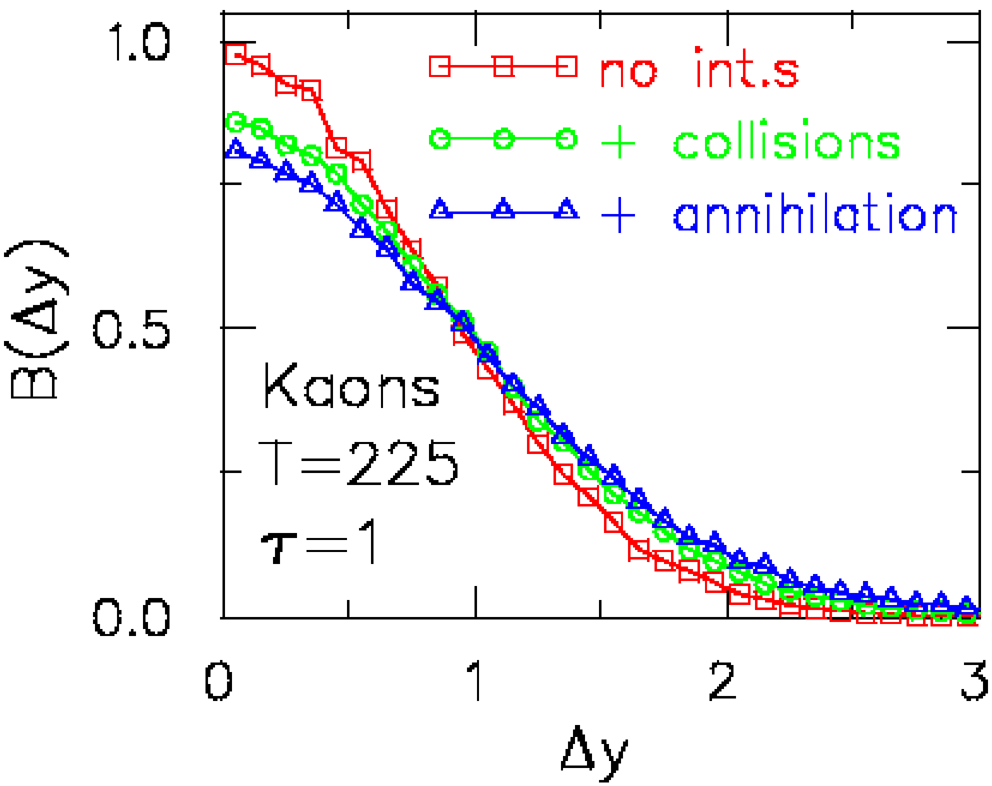
No diffusion when:

1. **No collisions, s=0.**
2. **Infinite collision rate**

Diffusion: A Simple Model

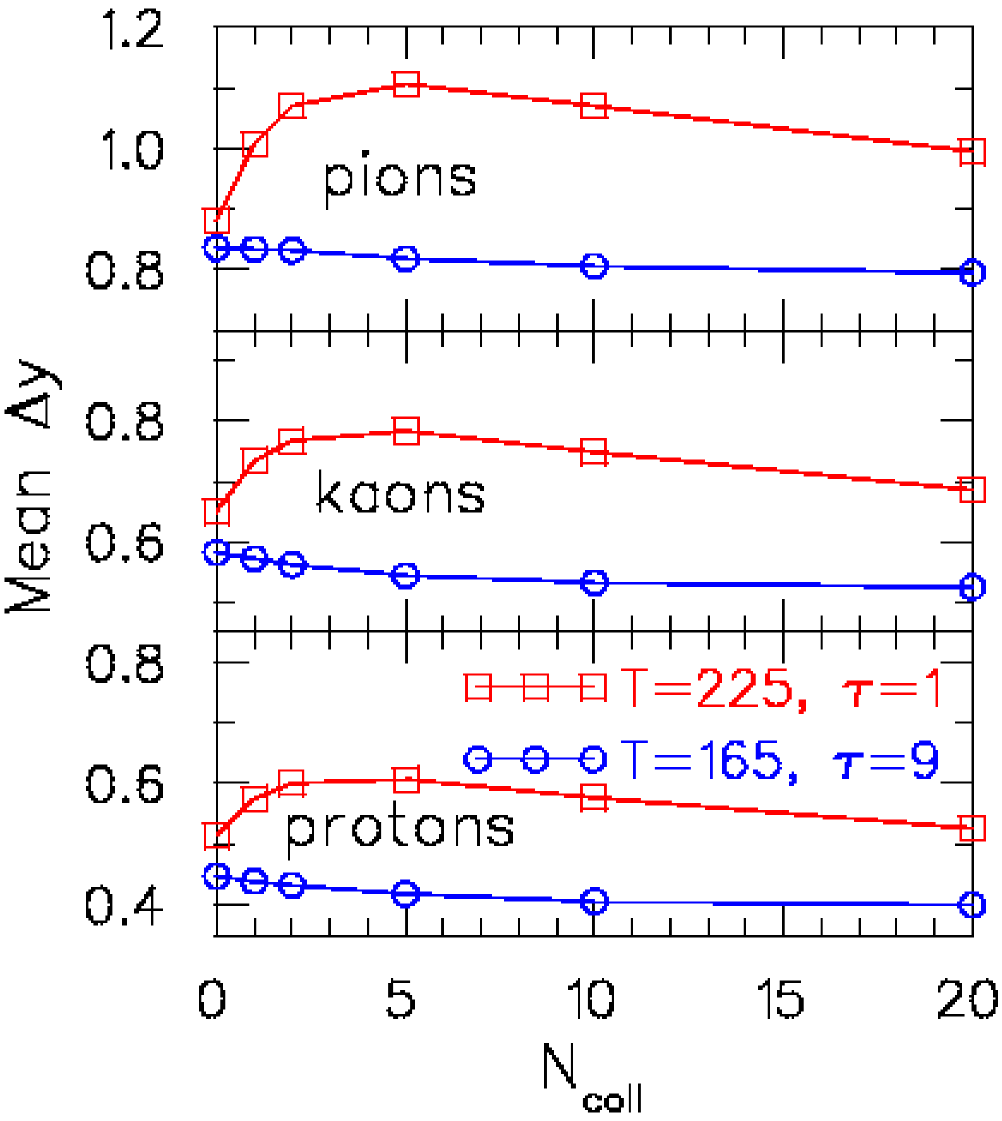
Procedure:

1. Generate a pair thermally at $\eta=0$, $\tau=\tau_0$.
2. Perform N_{coll} collisions randomly in ln τ.
3. Between collisions, move particles with straight-line trajectories.
4. Rethermalize to local T & flow velocity.
   $T(\tau_0=1\text{ fm/c}) = 225$ MeV
   $T(\tau_f=15\text{ fm/c}) = 120$ MeV
5. For Annihlations, convolute pairs.



Collisions & Annihilations magnify difference between early vs. late creation !

Model Summary



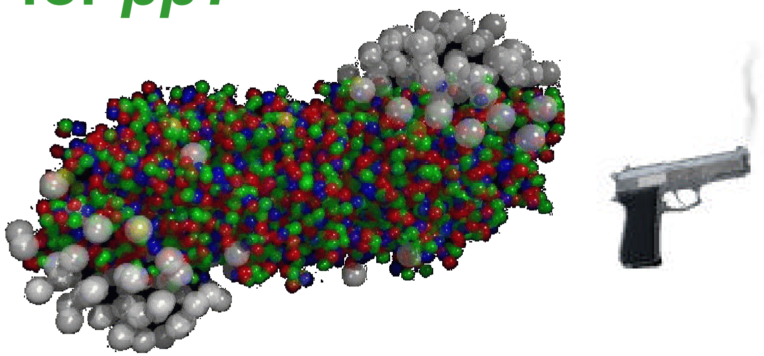
N_{coll} should equal:

~ 6 for t_0 = 1 fm/c,

~ 2 for t_0 = 9 fm/c

Even pions become sensitive to creation time.

What if Balance functions are narrower for *AA* than they are for *pp?*



RQMD-type descriptions are qualitatively wrong

AND

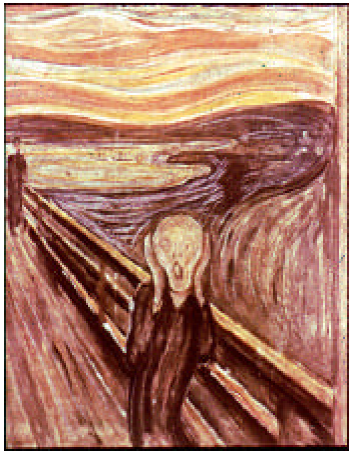
EITHER:

1. Late-stage production of charge
   - Change in degrees of freedom
   - QGP least exotic explanation

OR:

2. Anomalously short mean free paths
   - would be contrary to common wisdom

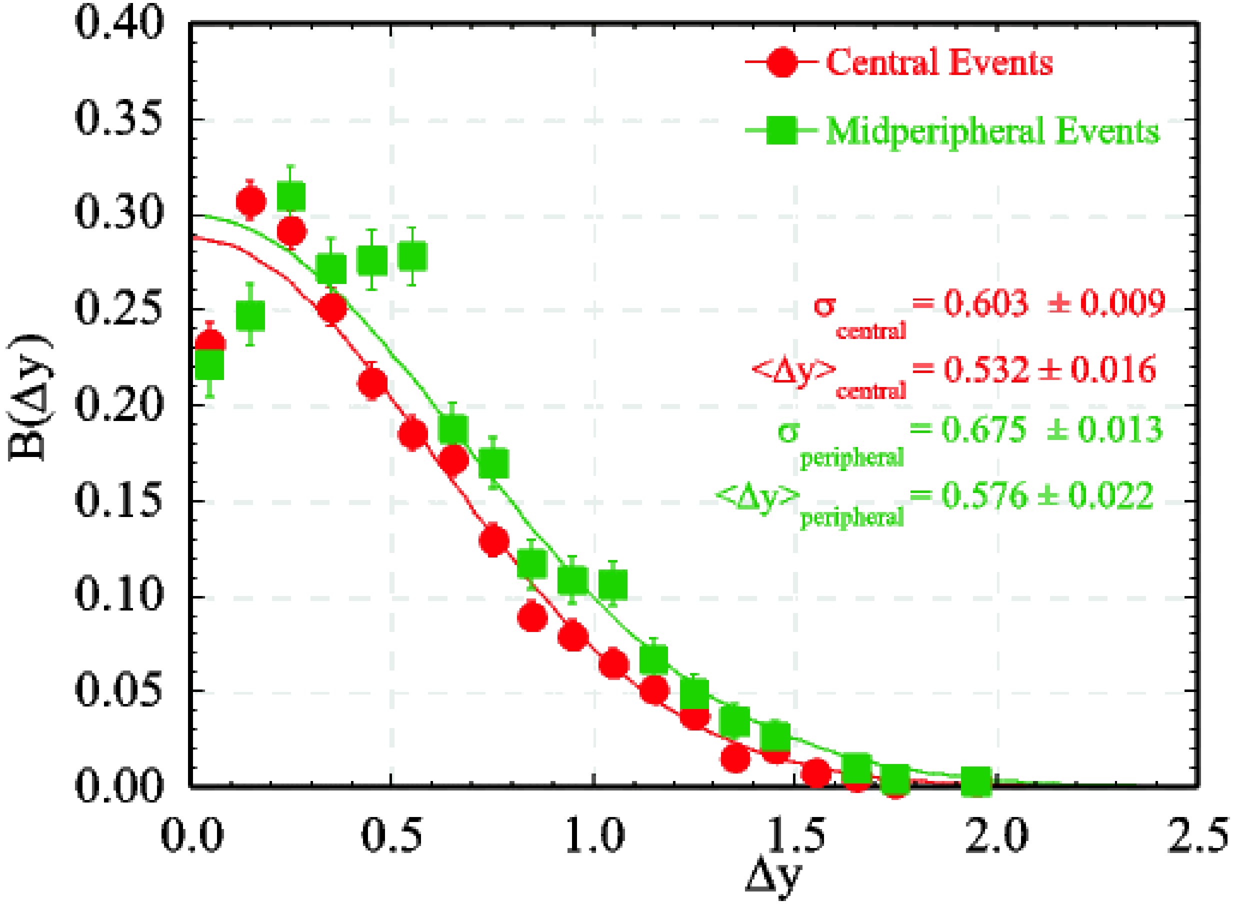
What if *AA* balance functions are NOT narrower?



- **Gluonic modes did not contribute to entropy**
- **No dramatic change in degrees of freedom.**
- **Canonical strangeness enhancement explanations are wrong.**
- **J/Ψ & Jet-quenching phenomenology are misguided.**

Preliminary STAR Results

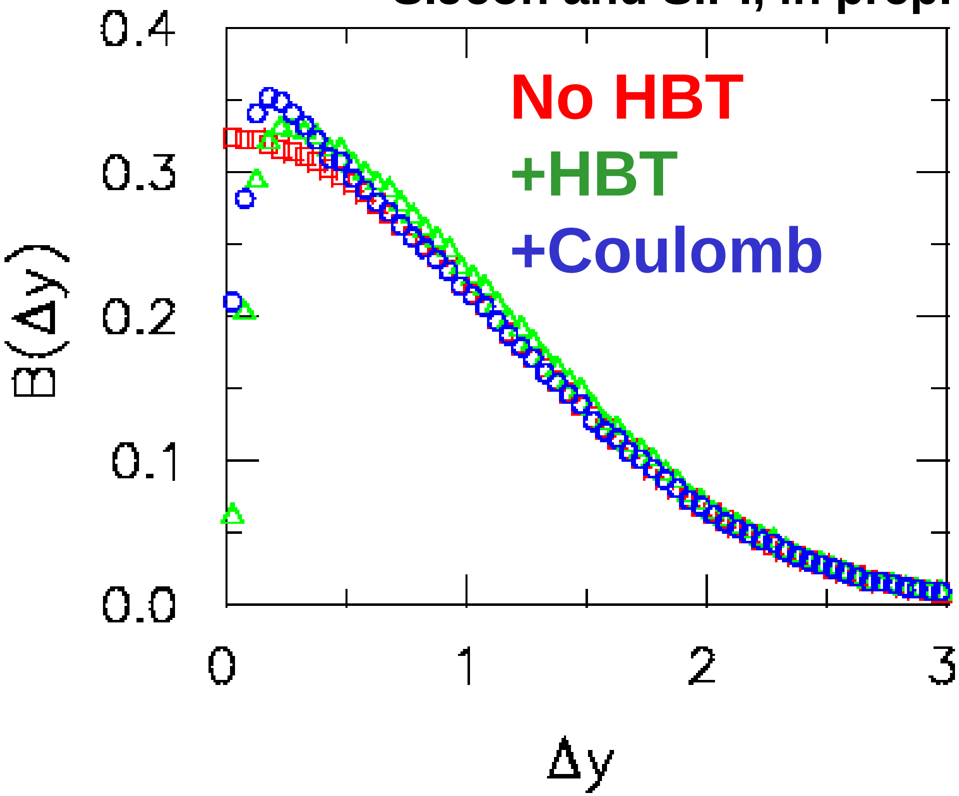
Identified Pions



More Central Collisions → Narrower Balance Functions !!!

The HBT Hole

S.Jeon and S.P., in prep.



HBT Weight:

- **Use parameters to get weight: T=190 MeV, λ=.7, R_{inv}=7 fm**
- **Dip at small Δy**
- **Applied to non-partners**
- **Proportional to *dn/dy***
- **Does not change norm.**
- **No significant change in $\langle \Delta y \rangle$**
- **Dip similar to that seen by STAR**

STAR Summary

	Central Data	Midperipheral Data	HIJING GSTAR Central
Charged pairs	σ=0.564±0.005 $\langle\Delta\eta\rangle$=0.555±0.011	σ=0.654±0.009 $\langle\Delta\eta\rangle$=0.612±0.017	σ=0.726±0.015 $\langle\Delta\eta\rangle$=0.659±0.026
Pion pairs	σ=0.603±0.009 $\langle\Delta y\rangle$=0.532±0.016	σ=0.675±0.013 $\langle\Delta y\rangle$=0.576±0.022	σ=0.706±0.011 $\langle\Delta y\rangle$=0.602±0.035
Kaon pairs	σ=0.350±0.031 $\langle\Delta y\rangle$=0.435±0.075	σ=0.391±0.047 $\langle\Delta y\rangle$=0.423±0.115	σ=0.743±0.096 $\langle\Delta y\rangle$=0.500±0.189

QUANTITATIVELY consistent with
HIJING → Thermal Production in Late Stage

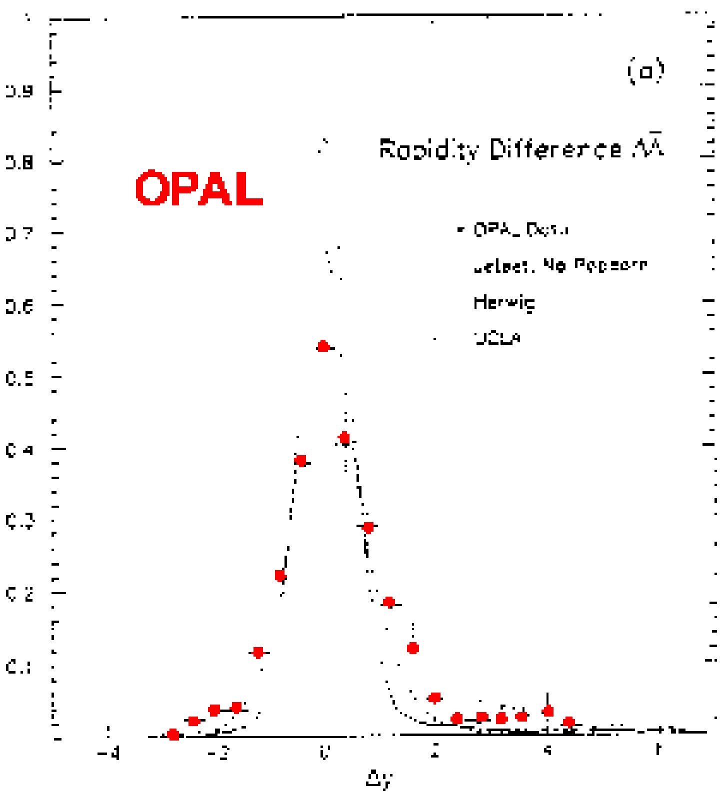
Can We Convict the QGP?

1. **Look at *pp* collisions.**
2. **Analyze K^+K^- and $p\bar{p}$ balance functions.**
3. **Measure p_t dependence.**
4. **Analyze as functions of $\Delta\phi$, Δp_t, Q_{inv}.**
5. **Role of transverse collective flow.**
6. **Quantitatively understand normalization:**
   - **Experimental acceptance**
   - **Interplay between acceptance and spectra.**
   - **Loss of partners to other channels,**

     e.g., π^+ balancing partner could be K^-.

All could be accomplished in next 12 months.

Balance Functions from Jets



- Similar analyses performed with:
  - ppdata:
    D. Drijard et al., NPB **155** (1979) 269.
    D. Drijard et al., NPB **166** (1980) 233.
    I.V. Ajinenko et al., ZPC **43** (1989) 37.
  - eedata:
    R. Brandelik et al., PLB **100** (1981) 357.
    M. Althoff et al., ZPC **17** (1983) 5.
    H. Aihara et al., PRL **53** (1984) 2199.
    H. Aihara et al., PRL **57** (1986) 3140.
    P.D. Acton et al., PLB **305** (1993) 415.
- Several pairs analyzed, e.g. $\Lambda\bar{\Lambda}$.
- JETSET fits data.

Thanks to T. Sjöstrand for references!